GEOPHYSICAL MODEL OF MASSIVE SULFIDE DEPOSITS

COX AND SINGER MODEL Nos. 24a, 24b, 28a Compiler - **W.D. Heran**

A. Geologic Setting

Three major deposit types are included:

- Cyprus - hosted in marine mafic extrusive rocks
- Besshi - hosted in marine mafic extrusive rocks
- Kuroko - hosted in marine felsic to mafic extrusive rocks

Cyprus Massive Sulfide: Within ophiolite assemblage, commonly above diabase dikes localized within pillow basalts or mafic volcanic breccia. Deposits are podlike massive, iron, copper and zinc sulfides with an underlying sulfide stringer zone. May be adjacent to steep normal faults and overlain by Fe-rich bedded marine sediments (ochre).

Besshi Massive Sulfide: Possibly related to submarine hot springs and associated basaltic volcanism within rifted basin of volcanic island arc or back arc setting. Usually hosted in thinly laminated elastic terrigenous sediments or mafic tuffs. Deposits are thin, sheetlike bodies of massive to well-laminated sulfides, laterally extensive and tend to cluster in en echelon patterns. All known deposits occur in strongly deformed metamorphic terranes.

Kuroko Massive Sulfide: Within calc-alkaline volcanic island arc systems and Archean greenstone belts. Common near center and felsic top of volcanic-sedimentary sequence with tendency to occur in close proximity to each other or clusters. Pyritic siliceous rock (exhalite) may be marker horizon. Distinctly vertically zoned, massive copper- and zinc-sulfide bearing, stratiform body with underlying veins and stockwork of disseminated sulfides.

Note: all three types upon weathering may produce yellow, red and brown limonitic gossans.

B. Geologic Environment Definition

Remote sensing methods can help detect and map the extent of ultramafic belts and intrusive complexes by overall reflectance (albedo), thermal properties and geobotanical changes (Barrington, 1991; Longshaw and Gilbertson, 1975). Landsat TM data have been utilized to map and subdivide units of the Semail ophiolite in Oman (Abrams, 1987). Landsat TM data have been used on a regional and local scale to recognize syn- and post-volcanic structures, including first and second-order lineament faults and shear zones in Canadian greenstone belts (Carboni and others, 1991). TM data were used to map lithologies, limonitic and gossan surfaces and integrated with panchromatic air photos providing structural data and locations of volcanic centers (Volk and others, 1987). Aircraft multispectral scanner data have successfully mapped the distribution of iron-oxide species over known gossan outcrop in Australia (Fraser and others, 1987).

Aeromagnetic and regional gravity data have been used to define tectonic terranes in northern Michigan and Wisconsin (Klasner and others, 1985). High-resolution aeromagnetic surveys were useful in interpreting Precambrian bedrock beneath glacial cover in Minnesota (Chandler, 1985). Enhanced high resolution aeromagnetic and VLF data were utilized to map lithology and regional faults in the central volcanic belt near Buchans, Newfoundland (Kilfoil, 1989). Ophiolite belts are characterized by aeromagnetic data as en echelon belts of short wavelength, high gradient anomalies (Heinz, 1989), and chains of narrow local positive and negative anomalies (Menaker, 1981). Greenstone belts may be defined in aeromagnetic surveys as a regional magnetic low if the belt is magnetite-deficient, in other cases a high if it is magnetite-rich (Grant, 1985; Isles, Harman and Cunneen, 1988). A statistical analysis of regional magnetic and gravimetric parameters were used to evaluate regional deposit potential in greenstone areas in Canada (Favini and Assad, 1974). Regional gravity was used to define thrust faults in an island-arc terrane in Canada (Wilson and Brisbin, 1960). Airborne electromagnetic surveys have been widely used in favorable terrains for finding conductors (Seigel, 1977; Klein and Lajoie, 1992; Ward, 1967; 1970) and can be credited for the discovery of numerous massive sulfide deposits in Canada (Paterson, 1966; 1967; Fleming and Brooks, 1960; Mackay and Paterson, 1959; Podolsky, 1966) and Wisconsin (Schnenk, 1977; May and Schmidt, 1982; Mudrey and others, 1991).

C. Deposit Definition

Massive sulfide bodies are defined as a single mass containing between 50-80% metallic sulfide minerals. This fact almost always lends to a higher electrical contrast relative to its host. A variety of ground EM methods have been successfully applied, as follow-up to airborne surveys, including the frequency and time domain methods utilizing a broad band of frequencies and employing several coil configurations (Ward, 1966, 1979; Crone, 1966, 1979; and Strangway, 1966; McCracken, 1981; Klein and Jajoie, 1992; Zonge, 1992; Sinha and Stephens, 1987). Other electrical methods such as SP (Cifali and Whiteley, 1981; Moss and Perkins, 1981), resistivity (Quick and Cifali, 1981; Tyne and Whiteley, 1981), and IP (Hallof, 1966; 1992) have been widely used to locate and define deposit parameters. The presence of pyrhotite and/or magnetite in the mineral assemblage of the deposit (not always present) may cause a magnetic contrast with the host rock. Ground magnetic surveys are commonly used (Hood and others, 1979) if a subtle or strong airborne magnetic anomaly is obtained, to locate or outline ore zones. The magnetic method is credited for the discovery of the Pima ore body in Arizona (Heinrichs and Thurmond, 1956). Another inherent physical property of the massive sulfide is high density of the ore minerals. The gravity method although not normally used as a primary tool can play an important role in an integrated effort to check EM or electrical anomalies (Tanner and Gibb, 1979; West, 1992; Boyd and others, 1975; Barbour and Thurlow, 1982), outline the deposit, or estimate ore reserves (Templeton, 1981). A 2.8 mgal anomaly was obtained over the Faro deposit NWT Canada (Brock, 1973). Seismic refraction and reflection surveys have been used to map fault structures (Spencer and others, 1993) map ore zones (Cooksley, 1992) and as a screening method to distinguish between shallow orebodies and conductive shales or graphite zones (Hawkins and Whitely, 1981). Downhole electrical and gamma radiation methods were used at the Woodlawn deposit, Australia to effectively outline the deposit and log lithologies (Templeton and others, 1981; Hone and Young, 1981).

D. **Size and Shape of**	**Shape**	**Average Size/Range**
Deposit	lenticular to sheetlike; stringer, stockwork	$8.2x10^5m^3/5.1x10^4-8.7x10^6m^3$
Alteration	stringer zone or blanketing	

E. **Physical Properties** (units)	**Deposit**	**Alteration**	**Host**
1. Density (gm/cc)	3.9, 3-4.5[(2)]		*
2. Porosity (%)	.35, .2-.5[(2)]		*

3.	Susceptibility (10^{-6} cgs)	1200, 0-5400[2]	*
4.	Remanence (mA/m)	.8, .2-1.0[32]	*
5.	Resistivity (ohm-m)	1, .01-62	*
6.	IP Effect		
	chargeability (mv-sec/v)	45, 16-125[2]	*
	percent freq. effect (PFE)	5, 0-200[32]	*
7.	Seismic Velocity km/sec	1.4, 1.1-1.8[32] 3.2[10]	*
8.	Radiometric		
	K (%)	low-moderate	*
	U (ppm)	low	*
	Th (ppm)	low	*

F. Remote Sensing Characteristics

Visible and near IR: Iron-oxide species (goethite, hematite, etc.) have unique reflectance spectra and can be distinguished from other alteration or weathering products (Hunt, 1979). Near-infrared spectra (800-2500 nm) have been utilized to distinguish true and false gossans (Raines and others, 1985). Color composite images from Landsat MSS band ratio data have been used to successfully map ferric iron-bearing rocks (Segal, 1983). Airborne multispectral scanners have been applied to map rock types, soils, alteration and gossans in Australia (Fraser and others, 1987; Honey and Daniels 1986).

G. Comments

Ground follow-up surveys following regional exploration must eliminate extraneous sources of anomalies such as conductive graphitic zones. The choice of techniques to apply first will vary depending on host environment, minerals present, structural controls and target depth. The normally high electrical conductivity of massive sulfides makes the electrical or electromagnetic methods most frequently used (Ward, 1966). The electromagnetic method has been successfully used since the early 1920’s (Ward, 1979; Moss and Perkins, 1981). Gravity, magnetics and seismic methods are commonly used in an integrated exploration program. In general massive sulfide bodies are very dense, typically very conductive and frequently magnetic (Ward, 1966). Several geophysical case histories to note are: SEG Mining Geophysics, 1966; Case Histories of Mineral Discoveries, v. 3, AIME, 1991; and Geophysical Case Study of the Woodlawn orebody, New S. Wales, Australia, 1981.

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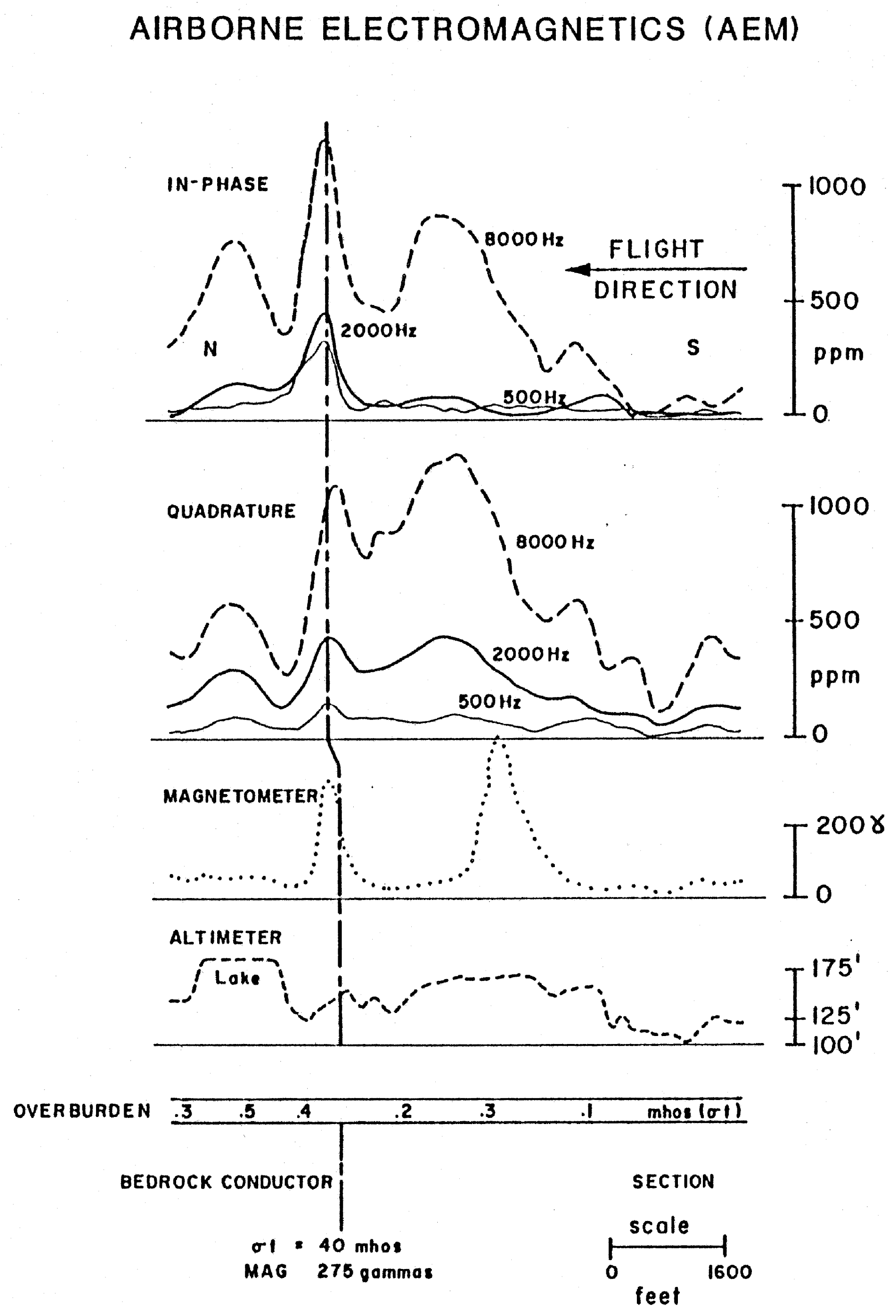


Figure 1. Three-frequency airborne electromagnetic (AEM), and magnetic data over the New Insco massive sulfide deposit, Quebec, Canada. (modified from Becker, 1979)

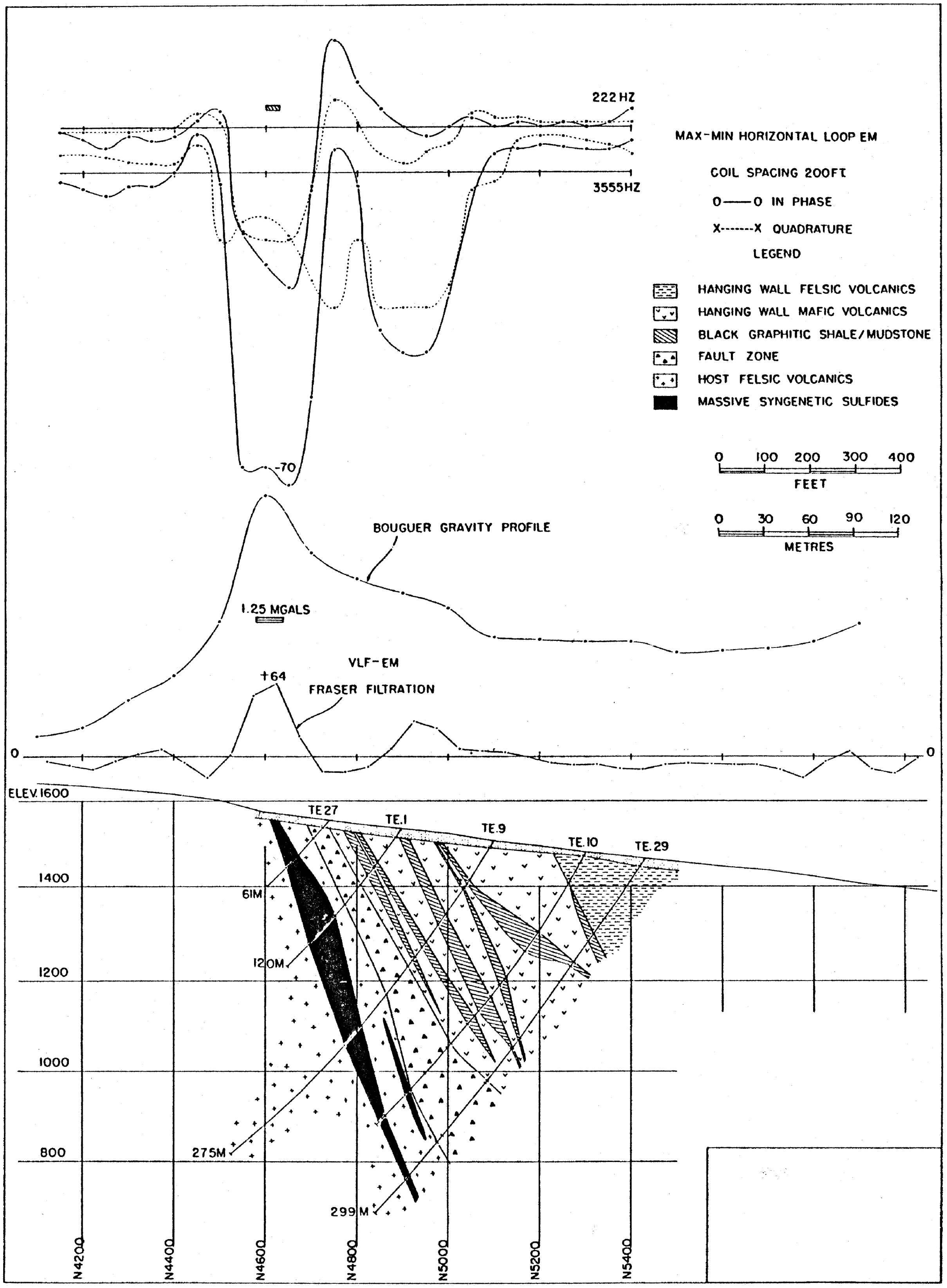
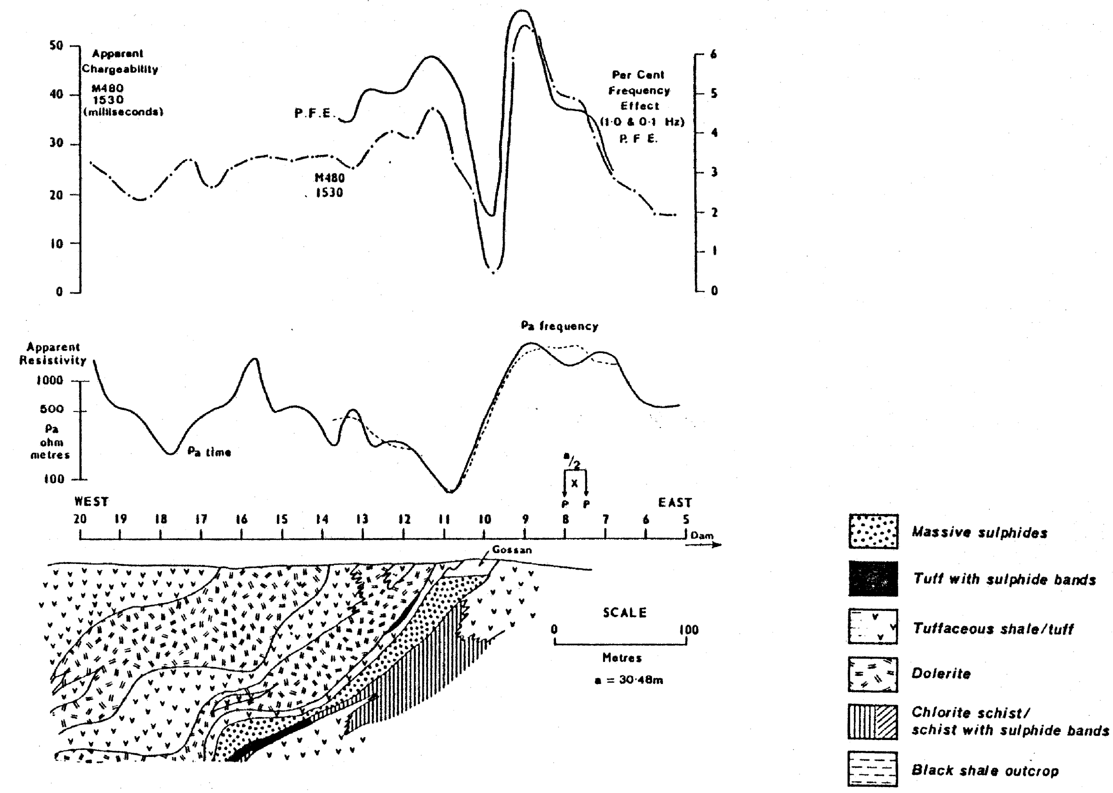


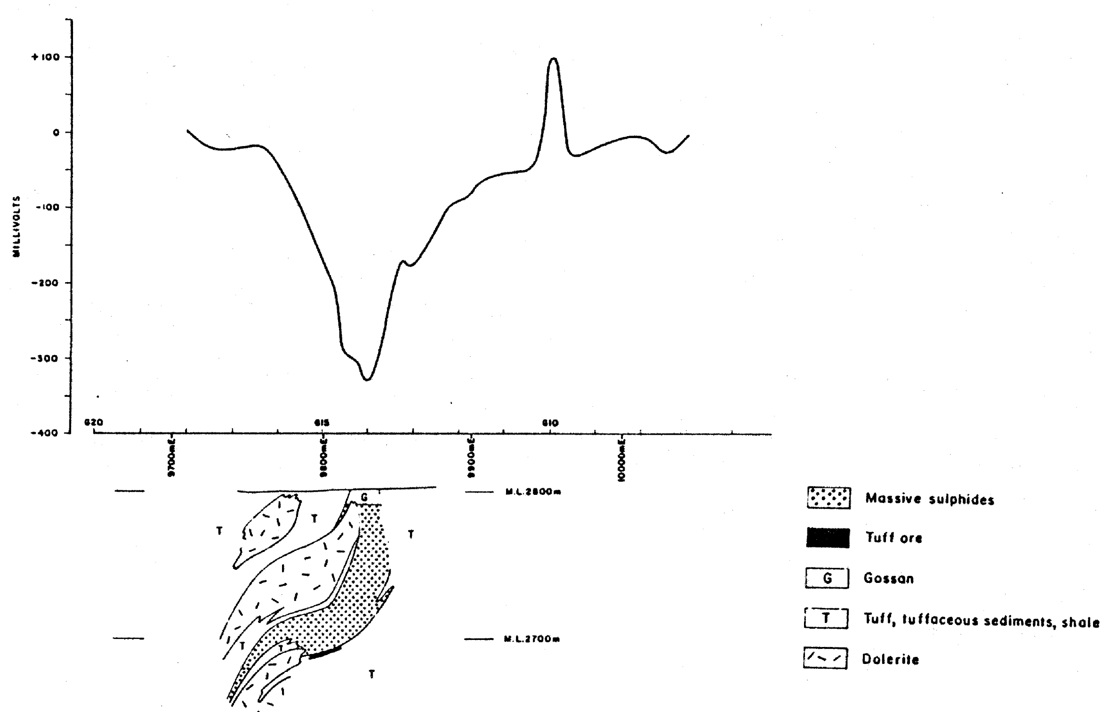
Figure 2. Electromagnetic data (horizontal loop and filtered VFL) and Bouguer gravity profile over the Tulks East massive sulfide, Newfoundland. (modified from Barbour and Thurlow, 1982)

INDUCED POLARIZATION



A

SELF POTENTIAL



B

Figure 3. Electrical surveys over the Woodlawn orebody. New South Wales, Australia. (A) Induced Polarization (IP) using gradient array in both time and frequency domain. (B) Self-potential profile showing an intense negative anomaly with a magnitude of about 300 mV. (modified from Cifali and Whitely, 1981; Tyne and Whitely, 1981)

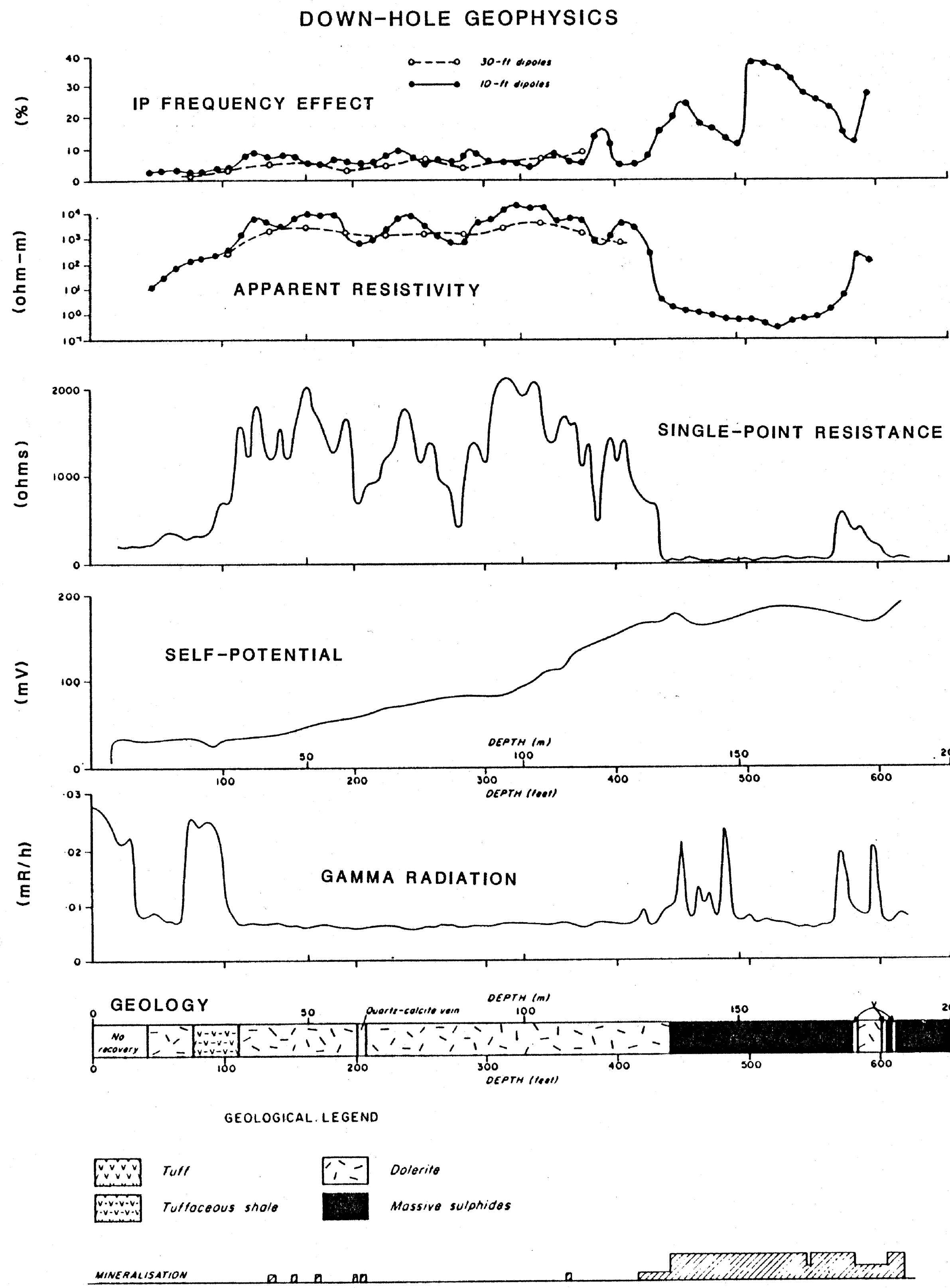


Figure 4. Drill hole electrical (frequency effect, apparent resistivity, single point resistance, self-potential) and gamma radiation logs along with drill core lithology from hole U256, Woodlawn orebody, New South Wales, Australia. (modified from Hone and Young, 1981)

GEOPHYSICAL RESPONSES OVER WOODLAWN

GEOPHYSICAL METHOD	NATURE OF GEOPHYSICAL RESPONSE				
	WEAK	MODERATE	STRONG	SIMPLE	COMPLEX
AIRBORNE					
Magnetics			NO ANOMALY		
HEM	###########				##########
Input	#####	#######			##########
Dighem II		########	######	#####	###
GROUND					
Electromagnetic (cw)			#######	########	
VLF		#############			
AFMAG			#######	########	
Audio MT					
Dip Angle					#########
Broadside	###########				
Fixed Transmitter			#######	########	
Slingram			#######	########	
Turam					
Large Loop			#######	########	
Small Loop			#######	########	
Electromagnetic (pulse)					
Crone PEM			#######	########	
Newmont EMP			#######	########	
MPPO 1			#######	########	
SIROTEM			#######	########	
Electrical					
SP			#######	#########	
Resistivity			#######	#########	
IP		#############			#########
MIP	#######	####			#########
Potential Field					
Magnetics			NO ANOMALY		
Gravity		#############		#########	
Seismic Refraction			#######		##########
DOWNHOLE					
SP			#######	#########	
Gamma Ray		########	######	#####	######
EM	###########				##########
Resistivity			#######	#########	
Mise-à-la-Masse			#######	#########	

TABLE 1. Table 1 shows the wide variety of geophysical methods used at the Woodlawn orebody (New South Wales) Australia, and a subjective classification of the geophysical responses, based on the magnitude of the response relative to background (modified from Malone and others, 1981).